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Climate and relief-induced controls on the temporal variability of denudation rates in a granitic upland

Raab, Gerald ; Egli, Markus ; Norton, Kevin ; Dahms, Dennis ; Brandová, Dagmar ; Christl, Marcus ; Scarciglia, Fabio

Abstract: How soil erosion rates evolved over the last about 100 ka and how they relate to environmental and climate variability is largely unknown. This is due to a lack of suitable archives that help to trace this evolution. We determined in situ cosmogenic beryllium-10 (¹⁰Be) along vertical landforms (tors, boulders and scarps) on the Sila Massif to unravel their local exhumation patterns to develop a surface denudation model over millennia. Due to the physical resistance of tors, their rate of exhumation may be used to derive surface and, thus, soil denudation rates over time. We derived soil denudation rates that varied in the range 0–0.40 mm yr⁻¹. The investigated boulders, however, appear to have experienced repositioning processes about 20–25 ka bp and were therefore a less reliable archive. The scarps of the Sila upland showed a rapid bedrock exposure within the last 8–15 ka. Overall, the denudation rates increased steadily after 75 ka bp but remained low until about 17 ka bp. The exhumation rates indicate a denudation pulse that occurred about 17–5 ka bp. Since then the rates have continuously decreased. We identify three key factors for these developments – climate, topography and vegetation. Between 75 and 17 ka bp, climate was colder and drier than today. The rapid changes towards warmer and humid conditions at the Pleistocene–Holocene transition apparently increased denudation rates. A denser vegetation cover with time counteracted denudation. Topography also determined the extent of denudation rates in the upland regime. On slopes, denudation rates were generally higher than on planar surfaces. By determining the exhumation rates of tors and scarps, soil erosion rates could be determined over long timescales and be related to topography and particularly to climate. This is key for understanding geomorphic dynamics under current environmental settings and future climate change.

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Keywords:	Granite landscapes, tor, boulder, denudation, cosmogenic nuclides

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Climate and relief-induced controls on the temporal variability of denudation rates in a granitic upland

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Abstract

Landforms such as boulders and tors adorn the upland of many granitic landscapes worldwide. We used in-situ cosmogenic nuclide techniques (^{10}Be) along vertical landforms (boulders, tors and scarps) on the Sila Massif in southern Italy to unravel their local exhumation patterns in order to develop a surface denudation model over the last 100 ka. Due to the physical resistance of tors, their rate of exhumation may be used to derive surface and, thus, soil denudation rates over time. Our results show that these denudation rates vary in the range of 0 – 0.37 mm year⁻¹. The investigated boulders have developed simultaneously but appear to have experienced repositioning processes about ~20 – 25 ka BP. The scarps of the Sila upland show a relatively rapid bedrock exposure within the last 8 – 15 ka with denudation rates of up to 0.40 mm year⁻¹. Overall, the denudation rates increased steadily after 75 ka BP but remained very low until about 17 ka BP. All landforms indicate a denudation rate pulse occurred about 17 – 5 ka BP independent of their position. Since then the rates appear to have continuously decreased. We identify three key factors for these developments – climate, topography and vegetation. Between 75 and 17 ka BP, climate was colder and drier than today. The rapid changes towards warmer and humid conditions at the Pleistocene-Holocene transition apparently influenced the increased denudation rates that we report. An increasingly dense vegetation cover (e.g. forest) with time appears to have counteracted the increased denudation. Topography also would have contributed to the extent of the past increase in denudation rates within the upland regime. As a consequence, slopes experienced higher denudation rates than planar surfaces. We show how these three environmental factors combine to control erosion of these granite upland surfaces.

1. Introduction

Granite shields and large massifs (Fig. 1) provide some of the most spectacular scenery around the world. These granitic landscapes are expressed in many ways, from convex hills (e.g. Sierra Nevada) to rock-cut plains (e.g. Australia). Alongside these grand landscapes, granite geomorphology is also associated with minor landforms such as boulders, tors or scarps (Migoñ, 2006), which occur in a variety of shapes and settings.

The distinction between these three landforms may appear straightforward, but the contrary is often the case. Scarps can be associated with cliffs, steep slopes or with displaced landforms (e.g. faults, landslides) that are commonly seen as bedrock outcrops along vertical or inclined surfaces that lack more detailed definition. Boulders are generally seen as rounded rock masses detached from bedrock with a diameter greater than 256 mm (Bates and Jackson, 1987) but sizes vary greatly from 25 cm to over 33 m in diameter. Boulders have also been defined as just 'more-or-less' rounded, isolated or clustered masses of standing rock (Linton, 1955).

The most ambiguous term of all of these is the 'tor'. Most famous for describing the castellated granite landscape of Dartmoor (England), the word is broadly used for large residual rocks (tower-like or dome-shaped), often castellated landforms (Linton, 1955). They characteristically have rounded summits or form convex ridges and seldom exceed 10 – 15 m in height (Migoñ, 2006). Thomas (1965) described them as spherically weathered boulders which are still rooted in bedrock.

Although such granitic landscapes are ubiquitous, the geomorphic literature mostly contains conceptual models with little empirical data (Linton, 1955; Migoñ, 2006; and references therein).

The timing and the forces that enable the formation of granitic outcrops are more often qualitatively described rather than quantitatively assessed (e.g. Twidale, 2002; Phillips et al., 2006). Depending on local conditions, boulders, tors and scarps may form within the saprolite. Rock tors and boulders have higher physical resistance than the surrounding soils or saprolite that are more easily weathered (Migón and Vieira, 2014). Therefore, in an eroding landscape, tors are exhumed over time by the lowering of the surrounding surface, through $D_{Surface}$, denudation processes consisting of W , weathering (i.e. conversion of bedrock to loose (erodible) material) and E , physical erosion (transport of mobile material by e.g. wind, water).

$$D_{Surface} = W + E \tag{1}$$

Thus, the rate of exhumation can be used to indicate denudation of the surrounding surface. Catchment-wide approaches are more commonly used to infer average erosion and/or denudation rates; however, such approaches make the coupling of denudation rates with specific landscape sites (e.g. slopes, ridges, planes) difficult, as landscapes may not evolve uniformly or linearly. Few studies have quantified the temporal development of particular landscape features (e.g. Gunnell et al., 2013, Heimsath et al., 2001). So far, granitic landforms such as tors, boulders and scarps have rarely been used as an environmental archive to trace rates of surface and relief development (Raab et al., 2018).

Vertical age profiles along tor surfaces allow the determination of their exhumation history and subsequently the calculation of surface denudation rates over several time intervals (continuous and over millennia; Heimsath et al., 2001; Wakasa et al., 2006; Raab et al., 2018). Applying the same technique to boulders and scarps enlarges the possibilities and enables comparisons among local formation patterns. Consequently, we use tors, boulders and scarps of a granitic landscape to explore surface lowering over time and, by extrapolation, denudation rates (predominantly erosion) over time. Due to the fact that tors, boulders and scarps are more physically and chemically resistant than the saprolite or soil, surface denudation causes their exhumation over time. By deriving in situ ¹⁰Be surface exposure ages along the these geomorphic landforms, we attempt to trace rates of surface lowering and, thus, soil denudation rates during the Holocene and part of the Pleistocene. We assume that denudation rates vary on both temporal and spatial scales. On eroding landscapes (and depending on the topographic position of tors, boulders or scarps), the signal intensity will most likely vary. Climate and vegetation patterns will have substantially varied over time (last 10 – 100 ka) in many parts of mid-latitude environments. We therefore hypothesize that calculated soil erosion rates can be linked to both the topographic position and to general patterns of climate and vegetation variability.

2. Study area

The Sila Massif in Calabria (Italy) is an ideal geological and topographic setting for our study (Fig. 2) with tors, boulders and rock scarps. Vegetation here consists of grassland, conifer (pine, fir) and

deciduous trees (beech) (Sorriso-Valvo, 1993; Scarciglia et al., 2005a,b). The present-day moist and temperate climate is typical for upland Mediterranean zones with an annual average temperature of 9 – 12 °C and annual precipitation of 1000 – 1800 mm (Le Pera and Sorriso-Valvo, 2000). The landscape of the box-shaped plateau is characterised by wide-flat to gently-rolling paleosurfaces ranging between 1000 m and 1700 m a.s.l. that are bordered by steep slopes. The relief and drainage systems are controlled by N-S, E-W and NW-SE trending faults (Molin et al., 2004; Spina et al., 2007).

The geological setting (Fig. 2b) of the Sila upland plateau was created by the uplift of the Paleozoic plutonic and metamorphic basement rocks of the Calabride complex and its Miocene-to-Pleistocene sedimentary cover. Regional tectonic uplift has affected a relatively large area and caused the isolation of the Sila upland through a number of tectonic phases (Molin et al., 2004; Olivetti et al., 2012). The last uplift phase occurred around 300 – 400 ka BP (Olivetti et al., 2012). The acceleration of regional uplift here resulted in a number of uplift rate estimates: between 0.6 and 1 mm year⁻¹ (Olivetti et al., 2012), between 0.52 and 0.88 mm year⁻¹ (Corbi et al., 2009), and 0.65 mm year⁻¹ (Bintanja et al., 2005).

For such uplift rates, the weathering model of Thomas (1997) suggests that grus weathering slightly dominates over saprolite formation. Le Pera and Sorriso-Valvo (2000) described the local 50 – 60 m thick weathering mantle as 'arenite' and 'clayed grus'. Both saprolite and grus weathering mantles are identified in this region (Scarciglia et al., 2016). As a consequence of local long-term deep weathering processes followed by exhumation, granitic boulder fields, tors and steep scarps have developed here which are represented by a large assortment of granitic outcrops of different sizes and shapes. Various forms depicted in the weathering scheme of Migoñ (2013) are present (Raab et al., 2018). Tors and outcrops with chessboard-like joint structures are found mostly along ridge crests but also occur in slightly undulating areas and isolated small topographic basins.

Tors are free-standing rock outcrops that remain attached to the underlying bedrock and usually have heights of 4 – 6 m. Some collapsed tors occur as elongated boulders with lengths of 8 m or more. Boulders, however, hardly exceed diameters of more than 2.5 m and vary from nearly perfectly rounded to half-moon shapes. Boulders are found in clusters or as single isolates on low-

angle relief surfaces. They are spread across the plateau but are more often found along gentle ridges (Scarciglia, 2015). Scarps are found throughout the plateau on rather steep to gently sloping surfaces.

3. Materials and Methods

3.1. Sampling sites and experimental design

Our sampling area is in the centre of the Sila massif (Fig. 2a) and provides an ideal mix of all required geomorphic landforms: close proximity (Fig. 2c) within a well-defined spatial area with relatively small altitudinal differences. At the center of the sampling area is a small north-oriented basin with planation surfaces that are surrounded by gently-undulated ridges. Its highest extent in the south acts as a divide between the northward-draining upland basin (e.g. Cecita Lake) and the southern drainage to the lowlands. Extensively-scarped slopes are mainly found in the northern basin. Tors and boulders are spread all-over, but are concentrated on the surrounding ridges.

We sampled tors from different topographic positions. Steeper slopes were investigated using one tor at the southern part of the watershed, one at the northern part and one on the ridge itself. These tors were compared to two tors nearer the basin center with gentler slopes and to three boulders along the watershed ridge.

To determine surface denudation in this landscape, our ^{10}Be sampling focused on surface exposures along vertical rock profiles (Fig. 3). According to our hypotheses, we expected to detect different formation and exhumation patterns:

- the vertical sampling of tors should reveal the landscape's denudation rates and changes over time and as a function of their topographic position
- boulders will have a more complex exhumation process, because of their detachment from the bedrock.
- scarp probably provide the timing of the more younger denudation processes

3.2. Sampling of rocks for in-situ ^{10}Be dating

We sampled three boulders, five tors and three scarps (Table 1). An average of six 1 – 3 kg samples per tor were taken at different heights in order to assess the timing of their progressive,

possibly multistep, exhumation through time. Given their uneven morphology, two of the three scarps were investigated in more detail with up to seven samples. The sampling was carried out with an electric stone saw, hammer and chisel. Because cosmic rays are distinctly attenuated within the rock, production of cosmogenic isotopes is highest directly at the surface. We therefore sampled the uppermost 1 – 3 cm of the rock surface (Table 1). Since tors may have already interacted with cosmogenic rays before they appear at the ground surface, we also sampled belowground (up to 40 cm deep) to account for possible early subsurface ^{10}Be accumulation. This was necessary in order to constrain the exhumation models. The position (latitude, longitude, altitude) of the sampling sites was recorded with GPS and verified with topographic maps. Standard corrections were made for the geometry of the rock samples and the effect of topographic shielding at each location (Gosse and Philips, 2001).

3.2 Surface exposure dating laboratory procedure – ^{10}Be

The rock sample material was crushed and about 0.4 kg of the 0.6–0.25 mm fraction were collected and treated according to standard procedures (Kohl and Nishiizumi, 1992). The selected fraction was treated with *aqua regia* for up to 36 hours and iron oxides, organic material and carbonates were eliminated. The remaining mineral assemblage underwent a 1h-treatment with 0.4% HF. Afterwards we used a flotation system (Kitchener, 1984) to physically separate mica and feldspar components from quartz. Any remaining contaminants were removed with 4% HF leaching cycles (7 – 21 days). About 20–30 g of the obtained pure quartz were spiked with a ^9Be -carrier solution (Scharlau, BE03460100) and together dissolved in 40% HF. We isolated Be by using anion and cation exchange columns followed by selective pH precipitation (von Blanckenburg et al., 1996). The resulting $\text{Be}(\text{OH})_2$ was calcinated to BeO for 2 h at 850 °C and mixed with Nb powder before pressing it into Cu-targets. The ETH Laboratory of Ion Beam Physics AMS facility measured the targets. ETH used ^{10}Be standard S2007N with a nominal value of $^{10}\text{Be}/^9\text{Be} = 28.1 \times 10^{-12}$ calibrated to the Nishiizumi standard ICN01-5-1 with a revised nominal value of 2.709×10^{-11} (Christl et al., 2013; Kubik and Christl, 2010, Nishiizumi et al., 2007). The 1σ error of S2007N is 2.7% (Christl et al., 2013). The measured $^{10}\text{Be}/^9\text{Be}$ ratios were corrected for the ^{10}Be contribution of the Be-carrier ($^{10}\text{Be}/^9\text{Be}$ blank ratio: $3.00 \pm 0.87 \cdot 10^{-15}$). Exposure ages were

calculated using the cosmogenic nuclide online calculator v2.3 (Balco et al., 2008). The program uses a ^{10}Be half-life of $1.387 \pm 0.0012\text{Ma}$ (Chmeleff et al., 2010; Korschinek et al., 2010) and a sea level high latitude ^{10}Be production rate of $4.01 \text{ }^{10}\text{Be-atoms gram SiO}_2^{-1} \text{ year}^{-1}$ (Borchers et al., 2016). The production rate was corrected for latitude and altitude after the scaling scheme of Stone (2000) and further corrected for the sample thickness according to the depth profile of Brown et al. (1992) with an effective radiation attenuation length of 160 g cm^{-2} of Gosse and Phillips (2001) and a constant rock density of 2.7 g cm^{-3} . A variety of rock surface erosion rates were tested with no correction for snow. Related effects of geomagnetic field variations on the ^{10}Be ages are assumed to be negligible (Masarik et al., 2001; Pigati and Lifton, 2004).

3.3. Determination of surface denudation rates (D_{Surface})

Ages were calculated on the basis of a rock surface erosion rate between 0 and $0.001 \text{ mm year}^{-1}$, typical for cold (alpine) granite regions (Small et al., 1999), and were subsequently used for modelling the exhumation rate (height vs. age). Best regression fits were obtained with a polynomial (3rd order) or a logistic function (Lichter, 1998) given by

$$f(t) = \frac{a}{(1 + e^{b(t-c)})} + d \quad (2)$$

where $f(t)$ = height m (lowered surface), as a function of time, a = range of height m, t = time years, b = slope coefficient –, c = time of the maximal rate of change years, and d = asymptotic value m. The height-age relation of the exhuming tors was then modelled by taking the error ranges of the ^{10}Be measurements into account (external error), using Monte Carlo simulations and the previously noted regression fits.

The mathematical derivative of these functions then provided the rates of surface surface lowering and, thus, surface denudation (D_{Surface}) in millimetres per year. For this calculation, it was necessary to account for the age of the rocks' initial surface appearance (early subsurface ^{10}Be accumulation; t_s), as follows:

$$D_{\text{Surface}} = \frac{\partial f(t-t_s)}{\partial t} \quad (3)$$

4. Results

4.1 Boulders

The 11 boulder samples (Table 1) provided 10 surface exposure ages (Table 2) that vary from 8 ± 1 ka to 91 ± 11 ka (Fig. 4). All ages and ^{10}Be concentrations show broad variation at the same heights above ground. The oldest age was from the sample taken at the bottom of Boulder #1, while the youngest ages were from the top of Boulder #2. Using a surface erosion rate of $0.002 \text{ mm year}^{-1}$, the top sample (1.4 m) of Boulder #3 resulted in an age of 54 ± 5 ka, similar to the ages (42 ± 4 – 68 ± 7 ka) of samples taken at the half total height (0.76 – 1.28 m) at Boulder #1. Boulder #2 gives nearly identical ages at the top (22 ± 2 ka) and at the bottom (24 ± 3 ka) despite a height difference of 1.7 m.

4.2. Tors

The 30 samples collected from tors (Table 1) resulted in 24 ages ranging from 11 ± 2 ka to 106 ± 12 ka (Table 2). The range of ages obtained from the tors is similar to that of the boulders. Application of various surface erosion rates (0, 0.001 , $0.002 \text{ mm year}^{-1}$) resulted only in minor differences (about 2.6 ka) in the exposure ages. Use of a surface erosion rate of $0.002 \text{ mm year}^{-1}$ resulted in the following age-height relationships: 38 ± 4 ka at 4 m for tor #1, 106 ± 12 ka at 5.6 m for tor #2, 37 ± 4 at 3.5 m for tor #3, 32 ± 3 ka at 3.6 m for tor #4 and 33 ± 3 at 2.4 m for tor #5 (Fig. 6).

The series of vertical profile samples from the five tors showed a general increase in ^{10}Be concentration with increasing height above the surrounding ground surfaces (Fig. 6f). We observed no obvious morphologic features that would indicate the presence of abrupt changes to the ^{10}Be signal (e.g. exfoliation). Samples taken below the present-day surface to determine early subsurface ^{10}Be accumulation had similar atom counts to those samples taken from the land-surface level at the base of the tors.

Following Raab et al. (2018), we used the surface ages, and thus exhumation rates, of the individual tors to model the surface denudation rates (Fig. 8b,d,f; Fig. 9b,d). We calculated average exhumation rates ($\approx D_{\text{Surface}}$) of $0.062 \pm 0.037 \text{ mm year}^{-1}$, $0.044 \pm 0.023 \text{ mm year}^{-1}$, $0.046 \pm 0.036 \text{ mm year}^{-1}$, $0.062 \pm 0.035 \text{ mm year}^{-1}$ and $0.036 \pm 0.031 \text{ mm year}^{-1}$ for Tors #1–#5, respectively (surface erosion rate of $0.002 \text{ mm year}^{-1}$). From the greater heights and older ages of the samples from Tor #2, we were able to model soil denudation rates for the last ~100 ka. Tor #2 yielded unusually low

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2 246 soil denudation rates compared to the other tors. Between 20 – 25 ka BP (Fig. 8d), however, Tor
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4 247 #2 exhibits similar results to the others. Tors #1 and #3 have similar slope angles (~6 – 10°) and
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6 248 similar surface ages at similar heights. Consequently, both exhibit similar denudation rates (Fig.
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8 249 8b, f) in the range of 0.05 – 0.37 mm year⁻¹. The surface denudation rates derived from the
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10 250 exhumation rates of tors having slope angles of 0 – 2° (#4 and #5) are slightly lower (0.06 – 0.22
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12 251 mm year⁻¹; Fig. 9b, d).

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17 253 **4.3 Scarps**

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19 254 The 15 samples taken along scarps (Table 1) resulted in 11 measured ages ranging from 8±1 ka to
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21 255 15±2 ka (Table 2; Fig. 10). Scarp #1 yielded the oldest age, but only one sampled was measured
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23 256 here. Scarps #2 and #3 exhibit identical ages at their base (9±1 ka). The ages slightly increase
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25 257 with height up to 13±1 ka at Scarp #2. At Scarp #3, however, the top of the scarp still exhibited an
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27 258 age of 9±1 ka while the ages at the bottom are statistically identical to Boulder #3 (8±1 ka). The
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29 259 larger number of successfully dated samples from Scarp #2 (6 samples) enabled us to derive an
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31 260 age-height model and subsequently a soil denudation trend model, which integrated the results
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33 261 from the individual samples of Scarp #1 (1 sample) and #3 (4 samples). The denudation rates
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35 262 range from 0.06 to 0.40 mm year⁻¹ with a peak denudation rate at ca. 4 ka BP (Fig. 9f).

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40 264 **5. Discussion**

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42 265 **5.1 Boulders**

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44 266 The complex age-elevation relationships imply that the boulders probably are not in their original
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46 267 positions and supports our hypothesis that some boulders have moved. Because of these
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48 268 inconsistencies, we were unable to derive exhumation rates from these boulders. Re-location due
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50 269 to a collapse of a larger structure, rock spallation, exfoliation (Scarciglia et al. 2005a, 2007) and
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52 270 toppling are plausible reasons for the various exposure ages. The selective local spheroidal
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54 271 weathering process is still continuing today (Scarciglia, 2015). Chemical weathering-driven multi-
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56 272 stage development of boulder landforms was proposed by Twidale (2002) through the formation of
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58 273 ‘corestones’ prior to exhumation (Migoñ and Prokop, 2013). This process is most notable in grus
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60 274 weathering environments, where the corestones emerge as boulders (Twidale and Romaní, 2005).

The fast removal of material surrounding the corestones, via e.g. physical erosion, could also be a relevant factor that leads to the emergence of boulders, as it reduces the time needed for a continuous chemical weathering.

Depending on the boulders' positions within the rock mass and the intensity of the erosion process, a broad spectrum of exhumation events are likely, from gradual (Boulder #3) to abrupt (Boulder #2). Early exposure of some boulder margins must have occurred ~90 – 100 ka ago. During this phase, denudation rates were low (Fig. 8d). Through constant denudation, progressively lower portions of boulders were exposed to cosmic rays. Thus, a second phase of exposure seems to have occurred ~50 – 70 ka ago (Fig. 4; Table 2) and coincides with the start of the increase in surface denudation (Fig. 8d). The toppling or collapse of a larger structure may have caused a repositioning of the boulders ~20 – 25 ka ago (Fig. 5), resulting in the younger ages found at the present-day boulder tops. A final denudation pulse, indicated by the extrapolated rates from the tors on the slopes on both sides of the watershed (Fig. 8b,f), exposed even lower parts of some boulders (e.g. Boulder #3) around 8 ± 1 ka. Because the boulder dataset is not conclusive, we propose that both processes, single corestone exhumation and toppling may be present.

5.2. Tors

We see the increases in ^{10}Be concentrations with height (Fig. 6f) as validation of our conceptual idea that tors were exhumed gradually over time (Fig. 7). A search of the literature shows that surface denudation rates using granite tors are about $0.01 - 0.02 \text{ mm year}^{-1}$ for cold (alpine) regions (Small et al., 1999) and $0.01 - 0.09 \text{ mm year}^{-1}$ in cool temperate climates (Heimsath et al., 2001; Phillips et al., 2006; Gunnell et al., 2013). Our average exhumation rates ($0.03 - 0.10 \text{ mm year}^{-1}$) fit well to those reported from the Dartmoor tors (Gunnell et al., 2013). Using river sediments as tracers, Olivetti et al. (2012) reported similar average erosion rates from cosmogenic ^{10}Be concentrations for the low-relief surfaces of the Sila upland ($0.09 \pm 0.01 \text{ mm year}^{-1}$ to $0.13 \pm 0.01 \text{ mm year}^{-1}$). Our approach, however, allows us to not only report an average value, but also to capture the variations over a time span of about 100 ka.

The exhumation rates of tors depend on their topographic position. Tors found at similar topographic positions exhibit similar denudation trends. Tors #1 and #3 are positioned along

backslopes and show higher overall rates (Fig. 8b,d) than Tors #4 and #5 (Fig. 9b,d), which are near the basin floor and along a lower surface gradient. These results show that tor archives can be used to decrypt differences in intensity and timing of denudation as well as variations among different slope segments over millennia. The regional character of the Sila uplift (Molin et al., 2004; Olivetti et al., 2012) corresponds with these general exhumation trends.

5.3 Scarps

Based on the exhumation patterns of the scarps, the soil denudation rates range from 0.06 to 0.40 mm year⁻¹ and differ from the tor-based rates in two ways: (1) their maximum denudation rates are slightly higher than those of the tors (Fig. 8b,f; Fig. 9b,d) and (2) the maximum soil denudation pulse seems to have occurred at about ~4 ka BP (Fig. 9f). Note that the denudation peak seen for the tors of the slopes and the planes is around ~9 – 14 ka BP (Fig. 8b,f; Fig. 9b,d). Denudation seems to have decreased along the slopes between ~4 – 9 ka BP while it increased at the scarp sites (Figs. 8 and 9). The exposure ages found lower on the scarps indicate that they represent the final stage of surface evolution and mark the final exhumation step of some tors (Fig. 6) and one boulder (Fig. 4c). We see this as a confirmation of our initial hypothesis, that scarps represent the youngest phase in surface evolution and differ in the timing of their formation when compared to the surrounding tors and boulders. This may be related to an episode of latest-stage headward fluvial incision toward the surrounding summits, a process which Molin et al. (2004) and Olivetti et al. (2012) have not considered. This interpretation also fits the concept that plateau evolution is partly a hillslope process (e.g. back-stripping; Molin et al., 2004; Olivetti et al., 2021).

5.4. Topography and denudation rates

So far, we establish that tors provide characteristic denudation rates within a landscape that depends on their topographic position. Boulders are not suitable for such an approach because of their detachment from the bedrock and the associated complex multi-stage exposure timing. Scarps provide only denudation trends for the most recent surface processes with similar characteristics as tors along slopes. We compare the individual modelled average denudation

rates with their topographic position (Fig. 12). To do this, we subdivided the relief of the study site into five distinct sections, based on their surface angle and position within the plateau (Fig. 12a). The 'ridgetops' of the watershed (Tor #2) mark the highest elevation with a minimum age of 100 ka. Exposure ages of nearby boulders indicate that they formed simultaneously (Fig. 2c). It appears that weathered material was transferred from the ridgetops to the 'slopes' on both the north-east (Tor #3) and the south-west (Tor #1) of the ridge. These two slope sections formed no later than 60 ka after the ridgetop. The drainage and thus material transport along the southern slope (Tor #1) is directed towards the lowland (Fig. 2) while the material of the northern slope (Tor #2) moves toward the small upland planes and basins where it can be partially re-deposited. The tors #4 and #5 are positioned in close proximity to a small local depression. Although these tors have only a minimum age difference of 5 ka to those on the slopes, their denudation trends are less pronounced (Fig. 12b). We interpret the lower trends as a result of exhumation buffering through sediment re-deposition. Material influx has possibly counteracted denudation at Tor #4 and #5 to slow the pace of their exhumation (Fig. 9b,d).

In summary, we see that D_{Surface} started to increase at 50 – 75 ka BP on the ridges (Fig. 8d), corresponding to the proposed second (70 ka BP) and third (50 ka BP) phases of boulder exposure (Fig. 5). A subsequent phase of denudation is indicated at about 10 – 25 ka from the ^{10}Be ages of the tors. This correlates with the initiation of the toppling (e.g. collapse of larger structure) period apparent from some of the boulders (Fig. 5).

Both tors and boulders are absent at the scarp sites and all are significantly older than the scarps. We propose that, during the major D_{Surface} pulse (~5 – 15 ka BP), the slopes were strongly eroded and that the modern surfaces started to be exposed to cosmic rays at about 12 ± 1 ka (Fig. 10). As the denudation rates of the surrounding area began to decrease at about 9 ± 1 ka (Fig. 12b), the production of loose material also must have decreased. Due to this reduction in sediment production, it is reasonable to assume that the fluvial system of the inner plateau removed the remaining regolith rather quickly, which resulted in a rapid exposure of the scarps. The resulting sediment would then have been relocated to the surrounding flanks and in the basins at the foot of the massif (Perri et al., 2012; Ruello et al., 2017; Russo Ermolli et al., 2017). The rapid removal of already disintegrated sediments would also explain the delayed increase in D_{Surface} at the hills

between 8 – 4 ka BP (Fig. 12b). Because of the significant decrease in $D_{Surface}$ at the ridgetops beginning at $\sim 9 \pm 1$ ka (Fig. 9e, 10), the youngest tor and boulder ages (bottom of Tor #2; boulder #3; Fig. 12a) match closely to those of the scarps of the hills. This suggests that the latest stage of the evolution of the Sila upland plateau was controlled by an initial episode of surface lowering followed by an early stage of river incision which then initiated erosion toward the summit of the landscape.

5.5. Responsible triggers for local denudation variations

Using the tors as an archive, the temporal variations of the denudation rates are clearly detectable (Fig. 8, 9). Several factors determine rates of denudation, including surface topography, geology, tectonics, biosphere, human activity and climate (Smithson et al., 2008). The temporal variability of the denudation rates thus suggests that the environmental drivers of landscape erosion also have changed. Furthermore, the detected changes depend on the topography, which indicates that the temporal trends depend on the relief position. Our approach and models enable us to investigate the causes of these variations over the last 100 ka (Figs. 8, 9, 12).

Because of the homogenous granitic basement (Fig. 2b), abrupt lithological changes do not occur here. Therefore, other than weathering-induced changes in rock density due to saprolite formation and local tectonic effects (shear zones, fault gauges), no transition exists to more easily eroded rock types that would have contributed to an increased $D_{Surface}$. Tectonic forces lifted the upland to its present elevation and caused a disequilibrium that had to be counterbalanced by denudation. Over the course of the investigated time span (~ 100 ka), the Sila Massif was uplifted by at least 50 m and possibly as much as 100 m (Olivetti et al., 2012; Corbi et al., 2009; Bintania et al., 2005). Our maximum denudation rate of $0.40 \text{ mm year}^{-1}$ (Fig. 9f) would only result in a calculated absolute denudation of 40 m (in line with estimates of Scarciglia, 2015), but only if it had been constant over the entire time span. By comparing the uplift rates to the average exhumation trend ($0.05 \pm 0.03 \text{ mm year}^{-1}$) of the vertical tor profiles, uplift appears even more dominant. Because the maximum $D_{Surface}$ is not large enough to compensate the minimum uplift-rate, we argue that the Sila Massif upland is still in disequilibrium, relative to its uplifting forces. Olivetti et al. (2012) also found the massif to be in a transient state of disequilibrium due to the strong and unsteady uplift that

occurred 300 – 400 ka BP. Furthermore, our interpretation of erosion and accumulation agrees with Olivetti et al. (2012) who assumed that counterbalancing erosion processes (up to ~ 0.92 mm year⁻¹ along the massif flanks; average of ~ 0.13 mm year⁻¹ at plateau) are only effective along the massif flanks and that 'pre-uplift' erosion rates are conserved in the flat upland area.

Tectonic uplift processes here laid the ground work for a potential increase in $D_{Surface}$ through accentuation of the relief leading to a predisposition toward erosion. Apparently, only the surrounding flanks appear to have responded (Olivetti et al., 2012) as the low $D_{Surface}$ values of the upland sites (Figs. 8, 9, 12) indicate that this area has not yet reacted to the tectonic uplift. We assume that the upland will remain relatively unaffected by the past uplift until the incision of creeks along the flanks become a dominant geomorphic process. The relatively young ages of the scarps suggest that this river incision is now at its earliest stage.

Besides relief, climate and vegetation also affect soil erosion. Vegetation ('biology') is, however, not a fully independent factor because it depends on climate. Therefore, a climate effect on erosion always also includes, to a certain extent, vegetation (in the case that there is no anthropogenic impact). The uplift of the plateau also contributed to an environmental change in flora and fauna. The plateau began as a Miocene lowland 5 Ma ago, then evolved to a low-relief landscape ~ 2.6 Ma and finally to an upland at about 400 ka ago (Olivetti et al., 2012). Based on pollen data, Fauquette and Combourieu-Nebout (2013) demonstrated that the Sila Massif had already reached a height of 1600 to 2100 m a.s.l. by 2.4 Ma. Furthermore, they described a change from a subtropical forest to an open-herbaceous biome as the uplift shifted the former humid climate towards a climate more dominated by stronger seasonal contrasts in temperature and precipitation. This change from a Thermomediterranean to an Oro- and Altimediterranean altitudinal organization (Ozenda et al., 1975; Bonin, 1981) has been identified in southern Calabria (Combourieu-Nebout, 1993).

In general, denudation forces are weaker under forest biomes and stronger in steppes, where the vegetation cover is temporally discontinuous (Allen et al., 1999). Forest biomes dominated the mountain regions of southern Italy (Lago Grande di Monticchio) during the periods 100 – 75 ka BP and 14 ka BP to present, while steppes dominated shortly around 95 ka BP and between 75 and 14 ka (Fig. 13; Allen et al, 1999). No detailed investigation of the vegetation history is available for

the Sila upland over the last 100 ka and so far, only palaeopedological investigations are available (Scarciglia et al. 2005b, 2008). Detailed soil charcoal analyses at Cecita Lake has enabled the reconstruction of vegetation changes for the Holocene (Moser et al., 2017). Fragments of charcoal in the soils surrounding Cecita Lake indicated the presence of an oak-dominated deciduous forest, which since has been replaced by mountain pine forest (Fig. 13; Pelle et al., 2013). Calibrated ^{14}C ages of charcoal samples only gave ages no older than 14 ka (Moser et al., 2017), which correlate with our surface exposure ages of the hills (8 – 15 ka; Fig. 9a). These data are consistent with those obtained from pollen analyses of a nearby upland palaeolake (Trifoglietti) of the Coastal Chain, located about 50 km northwest of our study area. Joannin et al. (2012) found evidence of an increased moisture from about 11 to 9.4 ka cal BP which could have enhanced erosion processes. At this site, a period with maximum humidity is recorded around 9.4 – 6.2 ka cal BP, followed by a general trend towards a drier climate until present. Previous soil age-estimates in the range of 16 – 67 ka BP with an average of 45 ± 11 ka BP (Fig. 13; Raab et al., 2017) in the Sila upland correspond to the age of the slopes (~40 ka; Fig. 12a). Additionally, a relatively short warmer and drier climate pulse from 30 to 50 ka BP enabled wooded steppes to form here (Fig. 13; Allen et al., 1999) which would have slightly balanced the denuding processes through a denser root network that would have withheld soil and sediment. Furthermore, soil development is strongly linked with volcanic ash influx during this time (Raab et al., 2018). Fertilization through volcanic ash-inputs (Pelle et al., 2013; Raab et al., 2017; 2018) may have enhanced this development at the upland, and might help explain the low D_{Surface} of Tor #2 (Fig. 8d; Fig. 12b).

Studies of human activity in southern Italy indicate the presence of organised human societies since 6 – 7 ka BP (Scarciglia et al., 2008; Pelle et al., 2013; Russo Ermolli et al., 2018). Allen et al. (1999) and Russo Ermolli et al. (2018) showed that the Apennine mountain chain and the Sant'Eufemia Plain (located southwest of the Sila Massif) experienced an increased influence of agricultural and forest clearance for the last 2 ka. A drastic increase in soil erosion has been recorded by Raab et al. (2018) due to more recent human activities.

6. Conclusions

Surface exposure dating (^{10}Be) along vertical rock profiles of granitic landscape forms (tors, boulders, scarps) revealed the temporal sequence of soil denudation processes and thus the controls on landscape evolution of the Sila Massif in southern Italy.

Tors provide a detailed insight into landscape evolution for the last 100 ka in southern Italy and allow us to more clearly understand and more effectively quantify the impacts that environmental factors have on landscape evolution here. We consider these granitic features to be a very useful landscape archive that provide evidence of variable rates of soil denudation over time and as a function of topographic position. Our modelled soil denudation rates vary across a range of ca. 0 – 0.37 mm year⁻¹, with the highest rates occurring around 10 – 25 ka BP.

Boulders, however, may not remain at a stable position and are therefore less suitable for dating these landscape processes. The investigated boulders in the Sila upland evolved parallel to the tors, although some appear to have experienced changes in position about 20 – 25 ka BP, making the calculation of soil denudation rates difficult or impossible at this point in time. The investigated rock scarps in the Sila upland are relatively young (8 – 15 ka) and show a rather abrupt bedrock exposure, probably due to an increase of the denudation forces during the last 15 ka, with a maximum at ~5 ka BP. Thus, the scarps at the Sila upland represent the final stage of surface evolution, probably triggered by an initial river incision, while boulder and tors are remnants of an older landscape where surface lowering (denudation) prevailed.

By piecing together the evolution of the individual landforms, we are able to reconstruct a denudation chronology for the Sila upland for the last 100 ka and to relate it to environmental processes that appear to drive the evolution of this landscape. Climate induced vegetation changes around 75 ka BP and rapid changes towards warmer and more humid conditions around 15 ka BP appear responsible for the increases in denudation rates where we observed them. Increases in the density of vegetation cover (e.g. forest) from 30 – 50 ka BP and particularly after 15 ka BP appears to have counteracted erosion during these periods. Topography was apparently a secondary factor controlling the extent of past variability in denudation rates in the upland. Our data suggest that slopes previously have experienced higher denudation rates than present-day planes and basins.

Overall, tors, scarps and boulders of granitic landscapes are excellent archives with which we may reconstruct environmental processes over time that may greatly improve our understanding of surface mass-flux processes.

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FIGURE 1 Granite landscapes around the world, differentiated between ancient shields and exhumed massifs. The map is modified after Migoñ (2006).

FIGURE 2 (a) Topographic map of the Sila Massif in southern Italy (after Raab et al., 2018). The sampling site of the study area near the Cecita Lake is marked as a white box (Geoportale Nazionale, Ministero dell'Ambiente, Italy). Additionally, normal and thrust faults are indicated (Olivetti et al. (2012)). (b) Geological overview map of the Sila Massif according to Liotta et al. (2008) and von Eynatten et al. (2015). The black frame indicates the sampling site. (c) Detailed position of sampled boulders, tors and bedrocks plotted on a Google maps (2017) surface model together with possible drainage patterns (blue arrows) on the basis of the steepness factors from Olivetti et al. (2012).

FIGURE 3 The sampling strategy for the individual landscape features (a) scarps, (b) boulders and (c) tors, is drawn in (d),(e),(f)., respectively.

FIGURE 4 Exposure ages (a,b,c) along the boulder profiles (Table 2). Their ^{10}Be concentrations are plotted as a function of height (d).

FIGURE 5 Proposed timing of events for some boulders (e.g. Boulder #1).

FIGURE 6 Exposure ages (a,b,c,d,e) along the tor profiles (Table 2). The overall ^{10}Be concentrations as a function of height (with related trend curve) of all samples are plotted in (f.)

FIGURE 7 Concept of tor exhumation according to the surface exposure ages (e.g. Tor #2).

FIGURE 8 Trend of Exposure ages as a function of tor height and derived soil denudation rates (D_{Surface}) using Monte Carlo simulations for Tor #1 (a and b), Tor #2 (c and d) and Tor #3 (e and f). RE = rock erosion.

FIGURE 9 Exposure ages as a function of sample height (tors and scarps) and derived surface denudation rates (D_{Surface}) using Monte Carlo simulations for Tor #4 (a and b), Tor #5 (c and d) and Scarps #1–#3 (e and f). RE = rock erosion.

FIGURE 10 Exposure ages (a – c) of scarps (Table 2). Their ^{10}Be concentrations are plotted as a function of height (with related trend curve) in d).

FIGURE 11 Conceptual model of surface lowering and exposure of scarps along the inner hills of the upland plateau.

FIGURE 12 (a) Relation between surface topography and denudation rates along the SW-NE investigation transect. (b) Comparison of modelled average denudation rates over time (Fig. 8 & 9) of the different surface relief sections (e.g. ridgetops, slopes, planes/basins, hills) and average erosion rates (calculated from cosmogenic ^{10}Be concentration using a material density of $2.6 \text{ [g cm}^{-3}\text{]}$) after Olivetti et al. (2012).

FIGURE 13 Model of local changes in climate (Allen et al., 1999) and vegetation (Allen et al., 1999; Pelle et al., 2013) for the last 100 ka. This concept also includes soil and charcoal ages and major findings of Raab et al. (2017) and Moser et al. (2017) to complement the series of surface evolution events.

TABLE 1 Sample characteristics of the investigated profiles along boulders, tors and scarps.

Samples series	Coordinates [WGS84]		Ground elevation	Rock type ¹	Sample thickness	Height above ground	Dip direction of rock surface	Dip angle of rock surface	Shielding factor
	Latitude	Longitude							
	[°N]	[°E]							
	[°N]	[°E]	[m a.s.l.]	[-]	[cm]	[m]	[°]	[°]	[-]
Boulder 1									
1-Top	39° 16' 51.6"	16° 32' 20.4"	1572	Granodiorite	2.00	2.25	040	10	0.999
2-Middle	39° 16' 51.6"	16° 32' 20.4"	1572	Granodiorite	3.00	1.28	325	70	0.613
3-Middle	39° 16' 51.6"	16° 32' 20.4"	1572	Granodiorite	3.00	1.02	250	80	0.879
4-Middle	39° 16' 51.6"	16° 32' 20.4"	1572	Granodiorite	3.00	0.76	345	85	0.558
5-Bottom	39° 16' 51.6"	16° 32' 20.4"	1572	Granodiorite	3.00	0.25	342	90	0.498
6-Bottom	39° 16' 51.6"	16° 32' 20.4"	1572	Granodiorite	3.00	0.10	220	70	0.490
Boulder 2									
1-Top	39° 16' 51.6"	16° 32' 20.7"	1572	Granodiorite	2.00	1.70	360	12	0.998
3-Middle	39° 16' 51.6"	16° 32' 20.7"	1572	Granodiorite	3.00	1.20	170	70	0.782
6-Bottom	39° 16' 51.6"	16° 32' 20.7"	1572	Granodiorite	9.50	-0.20	300	70	0.612
Boulder 3									
1-Top	39° 16' 35.6"	16° 32' 58.1"	1567	Granodiorite	1.00	1.40	047	7	1.000
6-Bottom	39° 16' 35.6"	16° 32' 58.1"	1567	Granodiorite	1.50	0.25	160	70	0.677
Tor 1*									
1-1-Top	39° 16' 06.7"	16° 32' 07.8"	1504	Granodiorite	2.00	4.00	150	10	0.999
1-2-Upper Middle	39° 16' 06.7"	16° 32' 07.8"	1504	Granodiorite	3.00	2.30	270	80	0.589
1-3-Middle	39° 16' 06.7"	16° 32' 07.8"	1504	Granodiorite	2.50	2.10	250	80	0.544
1-4-Lower Middle	39° 16' 06.7"	16° 32' 07.8"	1504	Granite	1.80	1.10	285	90	0.498
1-5-Bottom	39° 16' 06.7"	16° 32' 07.8"	1504	Granodiorite	2.00	0.20	290	40	0.473
1-6-Subsurface	39° 16' 06.7"	16° 32' 07.8"	1504	Granodiorite	1.00	-0.28	270	85	0.509

Tor 2*

2-1-Top	39° 16' 52.4"	16° 32' 22.9"	1572	Granodiorite	2.00	5.60	115	32	0.972
2-2-Upper Middle	39° 16' 52.4"	16° 32' 22.9"	1572	Granodiorite	3.00	4.60	115	80	0.654
2-3-Middle	39° 16' 52.4"	16° 32' 22.9"	1572	Granodiorite	1.50	3.30	225	70	0.704
2-4-Lower Middle	39° 16' 52.4"	16° 32' 22.9"	1572	Granodiorite	2.00	2.40	245	60	0.771
2-5-Bottom	39° 16' 52.4"	16° 32' 22.9"	1572	Granodiorite	3.00	0.30	360	90	0.501
2-6-Subsurface	39° 16' 52.4"	16° 32' 22.9"	1572	Granodiorite	9.50	-0.20	300	70	0.724

Tor 3*

3-1-Top	39° 17' 01.6"	16° 32' 17.0"	1569	Granodiorite	2.00	3.50	358	10	0.999
3-2-Upper Middle	39° 17' 01.6"	16° 32' 17.0"	1569	Granodiorite	3.00	2.10	170	85	0.504
3-3-Middle	39° 17' 01.6"	16° 32' 17.0"	1569	Granodiorite	2.00	1.30	165	90	0.498
3-4-Lower Middle	39° 17' 01.6"	16° 32' 17.0"	1569	Granodiorite	4.00	1.10	165	90	0.498
3-5-Bottom	39° 17' 01.6"	16° 32' 17.0"	1569	Granodiorite	2.00	0.20	170	80	0.607
3-6-Subsurface	39° 17' 01.6"	16° 32' 17.0"	1569	Granodiorite	3.00	-0.40	170	90	0.601

Tor 4

4-1-Top	39° 17' 56.9"	16° 32' 20.6"	1465	Granite	3.00	3.60	030	44	0.926
4-2-Upper Middle	39° 17' 56.9"	16° 32' 20.6"	1465	Granite	3.00	2.00	170	80	0.612
4-3-Middle	39° 17' 56.9"	16° 32' 20.6"	1465	Granodiorite	3.00	1.55	170	80	0.612
4-4-Lower Middle	39° 17' 56.9"	16° 32' 20.6"	1465	Granodiorite	3.00	0.85	170	80	0.612
4-5-Bottom	39° 17' 56.9"	16° 32' 20.6"	1465	Granite	3.00	0.38	170	80	0.612
4-6-Subsurface	39° 17' 56.9"	16° 32' 20.6"	1465		3.00	-0.30	170	80	0.612

Tor 5

5-1-Top	39° 18' 02.4"	16° 32' 12.4"	1475	Granite	2.00	2.40	088	26	0.986
5-2-Upper Middle	39° 18' 02.4"	16° 32' 12.4"	1475	Granite	1.50	1.60	071	21	0.969
5-3-Middle	39° 18' 02.4"	16° 32' 12.4"	1475	Granite	3.00	1.40	081	30	0.964
5-4-Lower Middle	39° 18' 02.4"	16° 32' 12.4"	1475	Granite	2.20	1.10	029	11	0.983

1	5-5-Bottom	39° 18' 02.4"	16° 32' 12.4"	1475	Granodiorite	1.80	0.26	160	55	0.845
2	5-6-Subsurface	39° 18' 02.4"	16° 32' 12.4"	1475	Granodiorite	1.80	-0.20	164	76	0.528
3										
4										
5	Scarp 1									
6	C1-Top	39° 19' 06.1"	16° 32' 12.8"	1360	Granite	3.00	1.49	285	10	0.932
7										
8										
9	Scarp 2									
10	A1-Top	39° 19' 06.4"	16° 32' 35.2"	1394	Granite	2.50	0.50	210	50	0.890
11	A2-Bottom	39° 19' 06.4"	16° 32' 35.2"	1394	Granite	2.50	0.10	110	80	0.534
12	B1-Top	39° 19' 06.4"	16° 32' 35.2"	1393	Granite	2.50	2.00	270	30	0.977
13	B2-Bottom	39° 19' 06.4"	16° 32' 35.2"	1393	Granite	2.50	1.00	270	90	0.492
14	C1-Top	39° 19' 06.4"	16° 32' 35.2"	1393	Granite	2.50	2.30	105	10	0.997
15	C2-Bottom	39° 19' 06.4"	16° 32' 35.2"	1393	Granite	2.50	1.10	210	70	0.714
16	C3-Subsurface	39° 19' 06.4"	16° 32' 35.2"	1393	Granite	2.50	-0.35	200	70	0.710
17										
18										
19										
20										
21										
22	Scarp 3									
23	A1-Top	39° 18' 43.2"	16° 33' 22.3"	1422	Granite	1.30	0.75	228	28	0.982
24	A2-Bottom	39° 18' 43.2"	16° 33' 22.3"	1413	Granite	2.00	0.20	195	30	0.978
25	B1-Top	39° 18' 43.2"	16° 33' 22.3"	1413	Granite	1.50	0.95	233	12	0.993
26	B2-Bottom	39° 18' 43.2"	16° 33' 22.3"	1413	Granite	1.50	0.15	055	40	0.991
27	C1-Top	39° 18' 43.2"	16° 33' 22.3"	1413	Granite	1.50	0.87	240	10	0.992
28	C2-Bottom	39° 18' 43.2"	16° 33' 22.3"	1413	Granite	3.00	0.64	240	30	0.977
29	C3-Subsurface	39° 18' 43.2"	16° 33' 22.3"	1413	Granite	1.80	-0.20	210	35	0.967
30										
31										
32										
33										
34										

35 *Data from Raab et al. (2018)
36 ¹Classification after Middlemost (1994)
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TABLE 2 Calculated exposure ages (+/- external uncertainty) based on ^{10}Be concentration (+/- error) and different rock surface erosion rates ($E0 = 0.000$ [mm year^{-1}], $E1 = 0.001$ [mm year^{-1}], $E2 = 0.002$ [mm year^{-1}]). Calculation was performed using the cosmogenic nuclide online calculator v2.3 (Balco et al., 2008).

Samples series	¹⁰ Be			Error	Heights	Calculated exposure ages of different rock surface erosion rates								
	Concentration					E0			E1			E2		
	[E+4 atoms g ⁻¹]					[a]			[a]			[a]		
Boulder 1														
1-Top	30.24	+/-	1.64	5.4	2.25	23000	+/-	2341	23448	+/-	2434	23919	+/-	2535
2-Middle	31.47	+/-	1.27	4.0	1.28	39258	+/-	3742	40582	+/-	4003	42032	+/-	4303
3-Middle	69.83	+/-	2.80	4.0	1.02	61382	+/-	5880	64733	+/-	6553	68625	+/-	7399
4-Middle	34.40	+/-	3.41	9.9	0.76	47197	+/-	6243	49129	+/-	6775	51287	+/-	7405
5-Bottom	28.40	+/-	2.11	7.4	0.25	43504	+/-	4977	45134	+/-	5364	46937	+/-	5817
6-Bottom	50.10	+/-	2.97	5.9	0.10	78674	+/-	8339	84265	+/-	9603	91069	+/-	11315
Boulder 2														
1-Top	26.52	+/-	1.36	5.1	1.70	21643	+/-	2168	22038	+/-	2249	22454	+/-	2336
6-Bottom	16.73	+/-	0.85	5.1	-0.20	23519	+/-	2348	23984	+/-	2443	24475	+/-	2546
Boulder 3														
1-Top	64.35	+/-	1.77	2.8	1.40	49367	+/-	4483	51502	+/-	4886	53903	+/-	5367
6-Bottom	7.03	+/-	0.35	5.0	0.25	7828	+/-	776	7878	+/-	786	7930	+/-	797
Tor 1*														
1-1-Top	44.99	+/-	2.51	5.6	4.00	36094	+/-	3716	37215	+/-	3954	38434	+/-	4224
1-2-Upper Middle	19.95	+/-	0.78	3.9	2.30	27097	+/-	2561	27717	+/-	2682	28376	+/-	2814
1-3-Middle	18.42	+/-	0.71	3.8	2.10	26987	+/-	2542	27602	+/-	2661	28255	+/-	2791
1-4-Lower Middle	16.60	+/-	0.67	4.0	1.10	26327	+/-	2502	26910	+/-	2616	27529	+/-	2740
1-5-Bottom	11.08	+/-	0.49	4.5	0.20	18479	+/-	1788	18763	+/-	1844	19059	+/-	1904
1-6-Subsurface	12.18	+/-	0.57	4.6	-0.28	18748	+/-	1831	-	+/-	-	-	+/-	-

1															
2	Tor 2*														
3	2-1-Top	112.44	+/-	4.39	3.9	5.60	89330	+/-	8576	96723	+/-	10097	106044	+/-	12269
4	2-2-Upper Middle	70.94	+/-	2.70	3.8	4.60	83960	+/-	8016	90408	+/-	9332	98390	+/-	11161
5	2-4-Lower Middle	30.12	+/-	1.49	4.9	2.40	29647	+/-	2946	30395	+/-	3098	31195	+/-	3267
6	2-5-Bottom	6.96	+/-	1.40	20.0	0.30	10518	+/-	2297	10609	+/-	2338	10703	+/-	2380
7	2-6-Subsurface	13.82	+/-	0.72	5.2	-0.20	15328	+/-	1538	-	+/-	-	-	+/-	-
9															
10	Tor 3*														
11	3-1-Top	45.45	+/-	1.04	2.3	3.50	34745	+/-	3097	35782	+/-	3287	36906	+/-	3501
12	3-3-Middle	18.18	+/-	0.56	3.1	1.30	27578	+/-	2518	28219	+/-	2638	28901	+/-	2770-
13	3-4-Lower Middle	19.73	+/-	0.57	2.8	1.10	28872	+/-	2616	29576	+/-	2747	30328	+/-	2892
14	3-5-Bottom	16.76	+/-	0.57	3.4	0.20	20882	+/-	1927	21248	+/-	1996	21931	+/-	2069
17															
18	Tor 4														
19	4-1-Top	34.14	+/-	0.84	2.5	3.60	30556	+/-	2736	31353	+/-	2882	32207	+/-	3045
20	4-2-Upper Middle	23.82	+/-	0.70	2.9	2.00	32088	+/-	2918	32963	+/-	3082	33906	+/-	3265
21	4-4-Lower Middle	13.24	+/-	0.46	3.4	0.85	17775	+/-	1646	18038	+/-	1696	18313	+/-	1749
22	4-5-Bottom	8.58	+/-	0.30	3.5	0.38	11493	+/-	1062	11603	+/-	1083	11715	+/-	1104
23															
24															
25															
26	Tor 5														
27	5-1-Top	37.73	+/-	1.31	3.5	2.40	31258	+/-	2903	32093	+/-	3062	32990	+/-	3240
28	5-2-Upper Middle	31.23	+/-	1.50	4.8	1.60	26164	+/-	2578	26745	+/-	2695	27362	+/-	2823
29	5-4-Lower Middle	33.04	+/-	1.11	3.4	1.10	27477	+/-	2538	28119	+/-	2659	28803	+/-	2793
30	5-5-Bottom	22.54	+/-	0.84	3.7	0.26	21661	+/-	2028	22057	+/-	2103	22472	+/-	2184
31	5-6-Subsurface	20.86	+/-	1.20	5.7	-0.20	31963	+/-	3314	32830	+/-	3499	33763	+/-	3706
32															
33															
34															
35															
36	Scarp 1														
37	C1-Top	15.05	+/-	0.81	5.4	1.49	14391	+/-	1459	14564	+/-	1494	14742	+/-	1532
38															
39															
40	Scarp 2														
41	A1-Top	11.16	+/-	0.67	6.0	0.50	10847	+/-	1134	10944	+/-	1154	11045	+/-	1176
42															
43															
44															
45															
46															

B1-Top	13.30	+/-	0.54	4.0	2.00	11793	+/-	1117	11908	+/-	1139	12027	+/-	1163
B2-Bottom	7.36	+/-	0.39	5.3	1.00	12831	+/-	1296	12967	+/-	1323	13107	+/-	1353
C1-Top	12.00	+/-	0.43	3.3	2.30	11294	+/-	1037	11400	+/-	1057	11509	+/-	1077
C2-Bottom	9.51	+/-	0.39	4.1	1.10	11494	+/-	1091	11603	+/-	1112	11716	+/-	1134
C3-Subsurface	7.01	+/-	0.35	4.9	-0.35	8501	+/-	840	8561	+/-	852	8622	+/-	864
Scarp 3														
A1-Top	9.82	+/-	0.46	4.7	0.75	8393	+/-	819	8345	+/-	830	8511	+/-	842
B1-Top	14.04	+/-	0.88	6.2	0.95	11896	+/-	1262	12014	+/-	1287	12136	+/-	1313
C1-Top	9.78	+/-	0.52	5.4	0.87	8288	+/-	837	8345	+/-	848	8403	+/-	860
C2-Bottom	10.35	+/-	0.80	7.7	0.64	9014	+/-	1039	9081	+/-	1055	9150	+/-	1071

*Data from Raab et al. (2018)

TABLE S1 Input data for the CRONUS online calculator (Balco et al., 2008).

	Latitude	Longitude	Elev.	Press.	Thick.	Density	Shielding	Erosion	Be ¹⁰	+/-	Be AMS	Al ²⁶	+/-	Al AMS
	[DD]	[DD]	[m]	flag	[cm]	[g cm ⁻²]	[-]	[cm yr ⁻¹]	[atoms g ⁻¹]	[atoms g ⁻¹]	standard	[atoms g ⁻¹]	[atoms g ⁻¹]	standard
Boulder 1														
B1-1	39.28055556	16.53861111	1572	std	2.00	2.65	0.9993462	0.0001	302422.62	16444.97	07KNSTD	0.000E+00	0.000E+00	KNSTD
B1-2	39.28055556	16.53861111	1572	std	3.00	2.65	0.6130000	0.0001	314671.19	12678.05	07KNSTD	0.000E+00	0.000E+00	KNSTD
B1-3	39.28055556	16.53861111	1572	std	3.00	2.65	0.8790000	0.0001	698344.01	28025.36	07KNSTD	0.000E+00	0.000E+00	KNSTD
B1-4	39.28055556	16.53861111	1572	std	3.00	2.65	0.55770156	0.0001	344030.00	34058.48	07KNSTD	0.000E+00	0.000E+00	KNSTD
B1-5	39.28055556	16.53861111	1572	std	3.00	2.65	0.49800000	0.0001	284000.00	21100.00	07KNSTD	0.000E+00	0.000E+00	KNSTD
B1-6	39.28055556	16.53861111	1572	std	3.00	2.65	0.49000000	0.0001	501100.00	29700.00	07KNSTD	0.000E+00	0.000E+00	KNSTD
Boulder 2														
B2-1	39.30066667	16.53677778	1475	std	2.00	2.65	0.9981940	0.0001	265127.58	13619.24	07KNSTD	0.000E+00	0.000E+00	KNSTD
B2-6	39.30066667	16.53677778	1475	std	9.50	2.65	0.6124795	0.0001	167379.96	8476.94	07KNSTD	0.000E+00	0.000E+00	KNSTD
Boulder 3														
B3-1	39.27658333	16.54905556	1567	std	1.00	2.65	0.992698516	0.0001	643518.04	17707.34	07KNSTD	0.000E+00	0.000E+00	KNSTD
B3-6	39.27658333	16.54905556	1567	std	1.50	2.65	0.6765712	0.0001	70289.95	3519.21	07KNSTD	0.000E+00	0.000E+00	KNSTD
Tor 1*														
T1-1	39.26852778	16.5353	1504	std	2.00	2.65	0.9986884	0.0001	449874.32	25147.16	07KNSTD	0.000E+00	0.000E+00	KNSTD
T1-2	39.26852778	16.5353	1504	std	3.00	2.65	0.5894925	0.0001	199524.28	7799.75	07KNSTD	0.000E+00	0.000E+00	KNSTD
T1-3	39.26852778	16.5353	1504	std	2.50	2.65	0.5435041	0.0001	184225.52	7059.29	07KNSTD	0.000E+00	0.000E+00	KNSTD
T1-4	39.26852778	16.5353	1504	std	1.80	2.65	0.4981389	0.0001	165951.50	6692.59	07KNSTD	0.000E+00	0.000E+00	KNSTD
T1-5	39.26852778	16.5353	1504	std	2.00	2.65	0.4731655	0.0001	110791.03	4936.78	07KNSTD	0.000E+00	0.000E+00	KNSTD

T1-6	39.26852778	16.5353	1504	std	1.00	2.65	0.5092840	0.0001	121791.35	5659.59	07KNSTD	0.000E+00	0.000E+00	KNSTD
Tor 2*														
T2-1	39.28138889	16.53972222	1572	std	2.00	2.65	0.9722750	0.0001	1124392.1 3	43924.80	07KNSTD	0.000E+00	0.000E+00	KNSTD
T2-2	39.28138889	16.53972222	1572	std	3.00	2.65	0.6539965	0.0001	709374.35	27041.14	07KNSTD	0.000E+00	0.000E+00	KNSTD
T2-4	39.28138889	16.53972222	1572	std	2.00	2.65	0.7713454	0.0001	301233.28	14884.82	07KNSTD	0.000E+00	0.000E+00	KNSTD
T2-5	39.28138889	16.53972222	1572	std	3.00	2.65	0.5009799	0.0001	69636.78	13956.20	07KNSTD	0.000E+00	0.000E+00	KNSTD
T2-6	39.28138889	16.53972222	1572	std	9.50	2.65	0.7240485	0.0001	138208.80	7185.71	07KNSTD	0.000E+00	0.000E+00	KNSTD
Tor 3*														
T3-1	39.28378889	16.53804167	1569	std	2.00	2.65	0.9991864	0.0001	454498.55	10355.57	07KNSTD	0.000E+00	0.000E+00	KNSTD
T3-3	39.28378889	16.53804167	1569	std	2.00	2.65	0.4980073	0.0001	181842.79	5558.30	07KNSTD	0.000E+00	0.000E+00	KNSTD
T3-4	39.28378889	16.53804167	1569	std	4.00	2.65	0.4980073	0.0001	187255.52	5303.40	07KNSTD	0.000E+00	0.000E+00	KNSTD
T3-5	39.28378889	16.53804167	1569	std	2.00	2.65	0.6074053	0.0001	167649.82	5651.15	07KNSTD	0.000E+00	0.000E+00	KNSTD
Tor 4														
T4-1	39.29915	16.53905556	1465	std	3.00	2.65	0.9259071	0.0001	341364.73	8407.53	07KNSTD	0.000E+00	0.000E+00	KNSTD
T4-2	39.29915	16.53905556	1465	std	3.00	2.65	0.6120609	0.0001	238184.52	6954.06	07KNSTD	0.000E+00	0.000E+00	KNSTD
T4-4	39.29915	16.53905556	1465	std	3.00	2.65	0.6120609	0.0001	132411.75	4613.81	07KNSTD	0.000E+00	0.000E+00	KNSTD
T4-5	39.29915	16.53905556	1465	std	3.00	2.65	0.6120609	0.0001	85754.31	2977.96	07KNSTD	0.000E+00	0.000E+00	KNSTD
Tor 5														
T5-1	39.30066667	16.53677778	1475	std	2.00	2.65	0.9856913	0.0001	377258.38	13092.27	07KNSTD	0.000E+00	0.000E+00	KNSTD
T5-2	39.30066667	16.53677778	1475	std	1.50	2.65	0.9693221	0.0001	312258.09	14949.18	07KNSTD	0.000E+00	0.000E+00	KNSTD
T5-4	39.30066667	16.53677778	1475	std	2.20	2.65	0.9825776	0.0001	330359.20	11089.76	07KNSTD	0.000E+00	0.000E+00	KNSTD
T5-5	39.30066667	16.53677778	1475	std	1.80	2.65	0.8451667	0.0001	225439.13	8378.27	07KNSTD	0.000E+00	0.000E+00	KNSTD

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T5-6	39.30066667	16.53677778	1475	std	1.80	2.65	0.5275316	0.0001	208559.19	11968.70	07KNSTD	0.000E+00	0.000E+00	KNSTD
Scarp 1														
S1-C1	39.31836300	16.53688100	1360	std	3.00	2.65	0.93206228	0.0001	150470.00	8125.15	07KNSTD	0.000E+00	0.000E+00	KNSTD
Scarp 2														
S2-A1	39.31843056	16.54310556	1393	std	2.50	2.65	0.8897977	0.0001	111550.88	6674.08	07KNSTD	0.000E+00	0.000E+00	KNSTD
S2-B1	39.31843056	16.54310556	1393	std	2.50	2.65	0.9769737	0.0001	132994.50	5378.45	07KNSTD	0.000E+00	0.000E+00	KNSTD
S2-B2	39.31843056	16.54310556	1393	std	2.50	2.65	0.4921216	0.0001	73626.48	3925.09	07KNSTD	0.000E+00	0.000E+00	KNSTD
S2-C1	39.31843056	16.54310556	1393	std	2.50	2.65	0.9971275	0.0001	129988.02	4307.61	07KNSTD	0.000E+00	0.000E+00	KNSTD
S2-C2	39.31843056	16.54310556	1393	std	2.50	2.65	0.7141295	0.0001	95121.77	3887.78	07KNSTD	0.000E+00	0.000E+00	KNSTD
S2-C3	39.31843056	16.54310556	1393	std	2.50	2.65	0.7104513	0.0001	70049.78	3450.22	07KNSTD	0.000E+00	0.000E+00	KNSTD
Scarp 3														
S3-A1	39.31200000	16.55619444	1422	std	1.30	2.65	0.9815712	0.0001	98178.22	4595.24	07KNSTD	0.000E+00	0.000E+00	KNSTD
S3-B1	39.31200000	16.55619444	1422	std	1.50	2.65	0.9926985	0.0001	140365.89	8761.17	07KNSTD	0.000E+00	0.000E+00	KNSTD
S3-C1	39.31200000	16.55619444	1422	std	1.50	2.65	0.9921959	0.0001	97831.67	5236.45	07KNSTD	0.000E+00	0.000E+00	KNSTD
S3-C2	39.31200000	16.55619444	1422	std	3.00	2.65	0.9769043	0.0001	103476.92	7974.30	07KNSTD	0.000E+00	0.000E+00	KNSTD

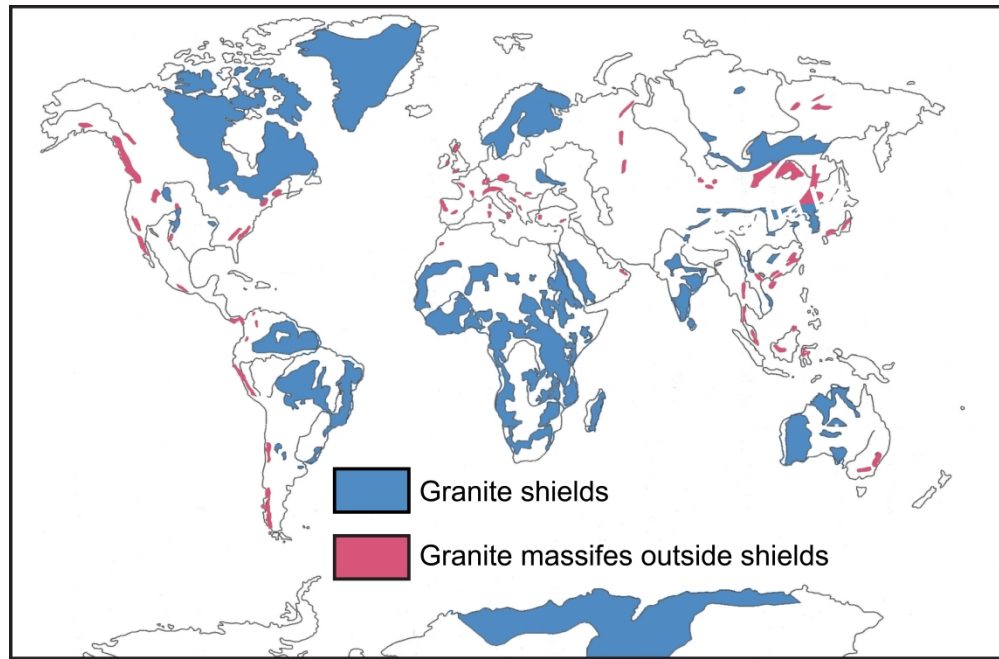


FIGURE 1 Granite landscapes around the world, differentiated between ancient shields and exhumed massifs. The map is modified after Migoń (2006).

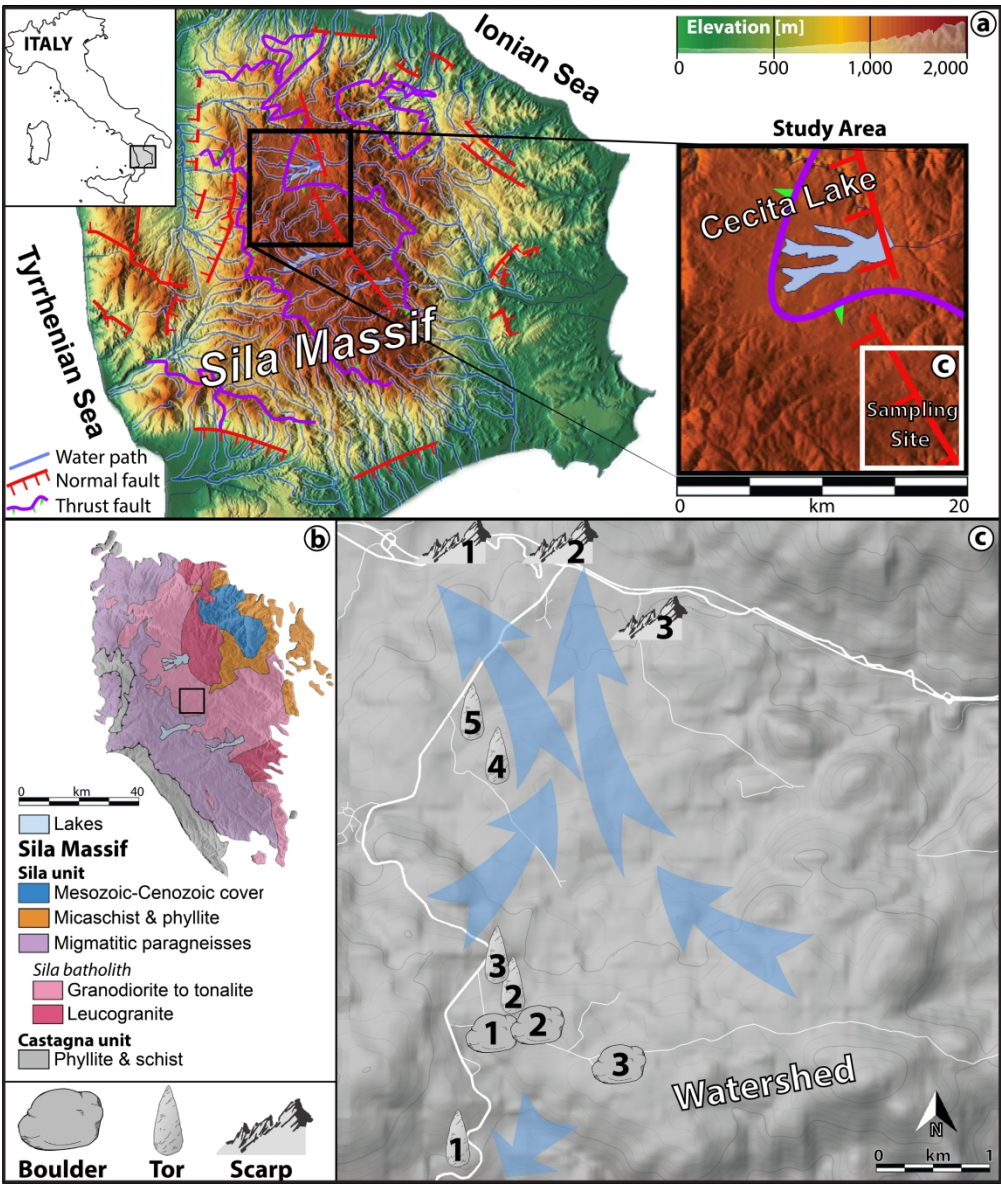


FIGURE 2 (a) Topographic map of the Sila Massif in southern Italy (after Raab et al., 2018). The sampling site of the study area near the Cecita Lake is marked as a white box (Geoportale Nazionale, Ministero dell'Ambiente, Italy). Additionally, normal and thrust faults are indicated (Olivetti et al. (2012)). (b) Geological overview map of the Sila Massif according to Liotta et al. (2008) and von Eynatten et al. (2015). The black frame indicates the sampling site. (c) Detailed position of sampled boulders, tors and bedrocks plotted on a Google maps (2017) surface model together with possible drainage patterns (blue arrows) on the basis of the steepness factors from Olivetti et al. (2012).

936x1103mm (72 x 72 DPI)

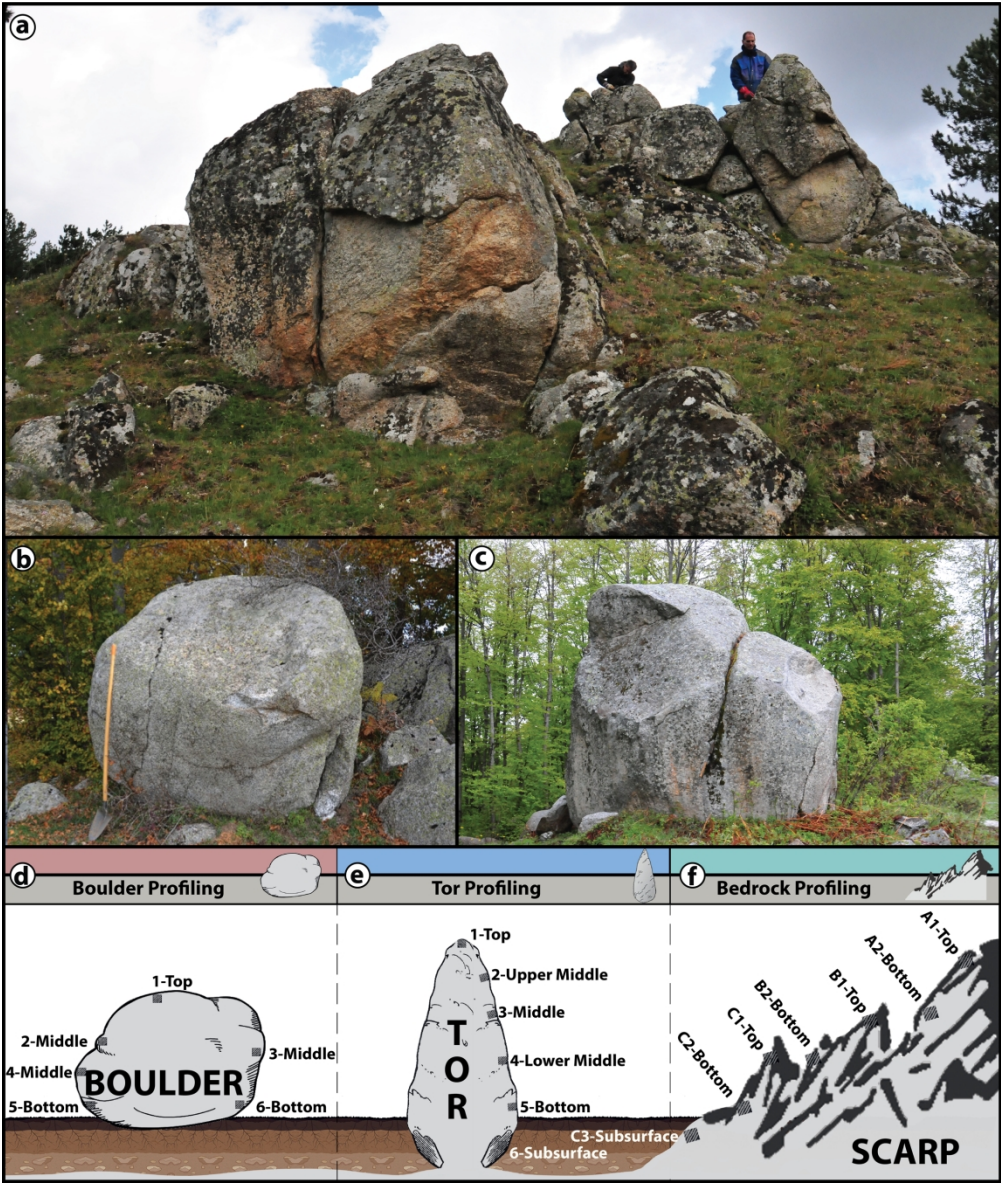


FIGURE 3 The sampling strategy for the individual landscape features (a) scarps, (b) boulders and (c) tors, is drawn in (d),(e),(f)., respectively.

819x966mm (72 x 72 DPI)

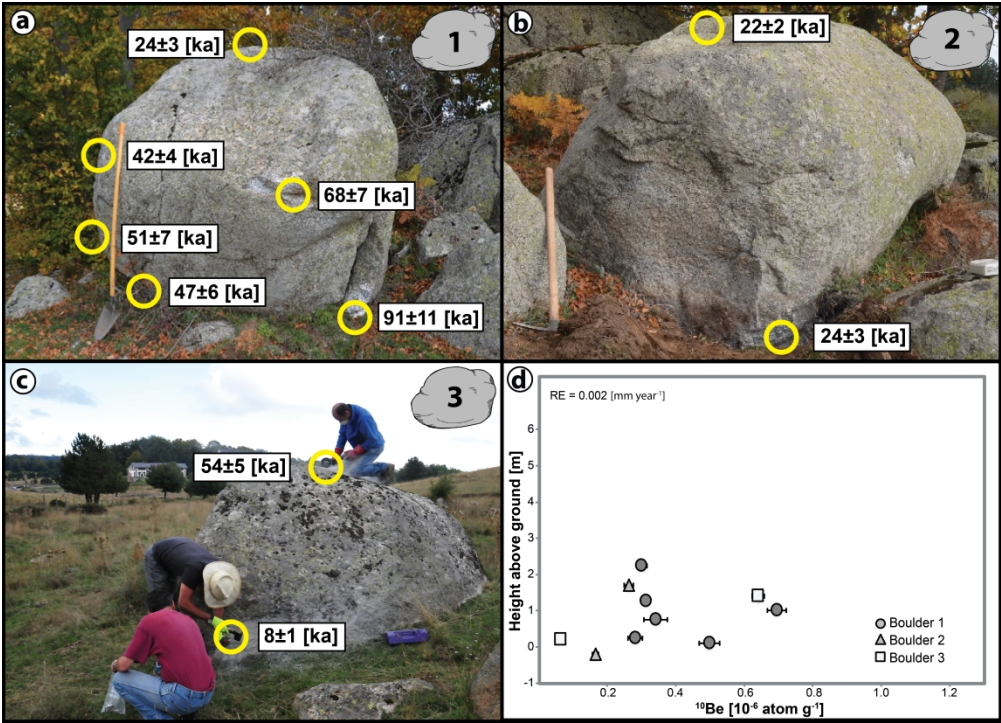


FIGURE 4 Exposure ages (a,b,c) along the boulder profiles (Table 2). Their ^{10}Be concentrations are plotted as a function of height (d).

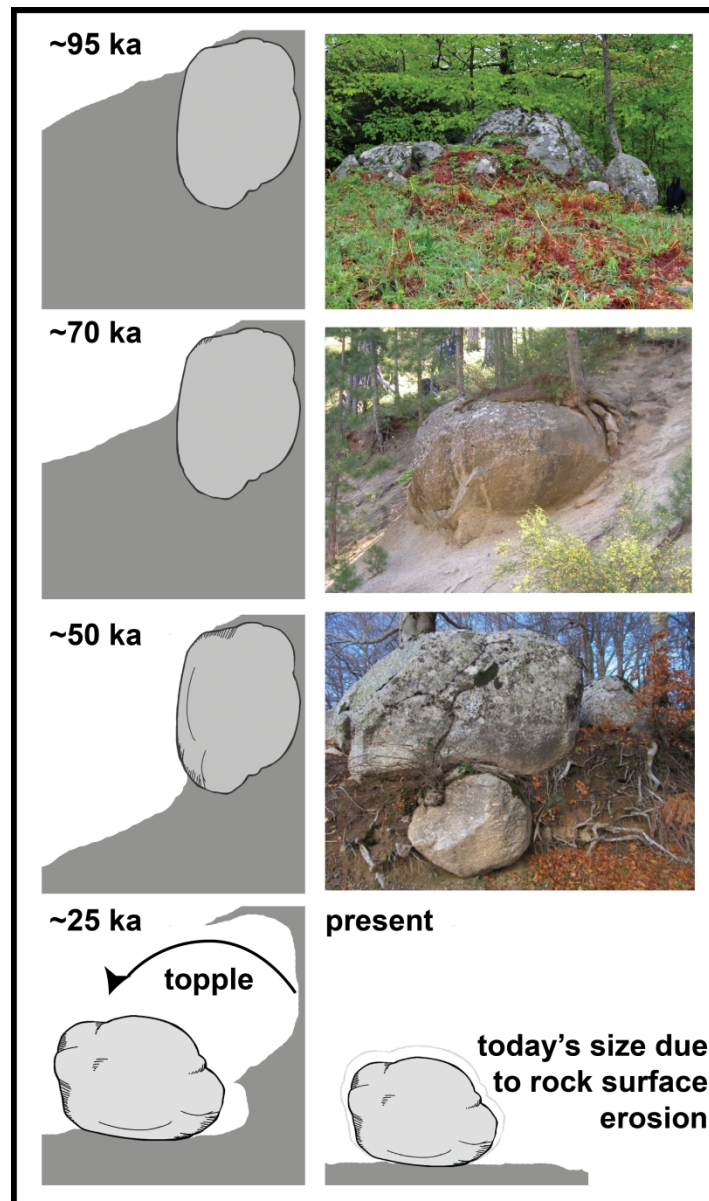


FIGURE 5 Proposed timing of events for some boulders (e.g. Boulder #1).

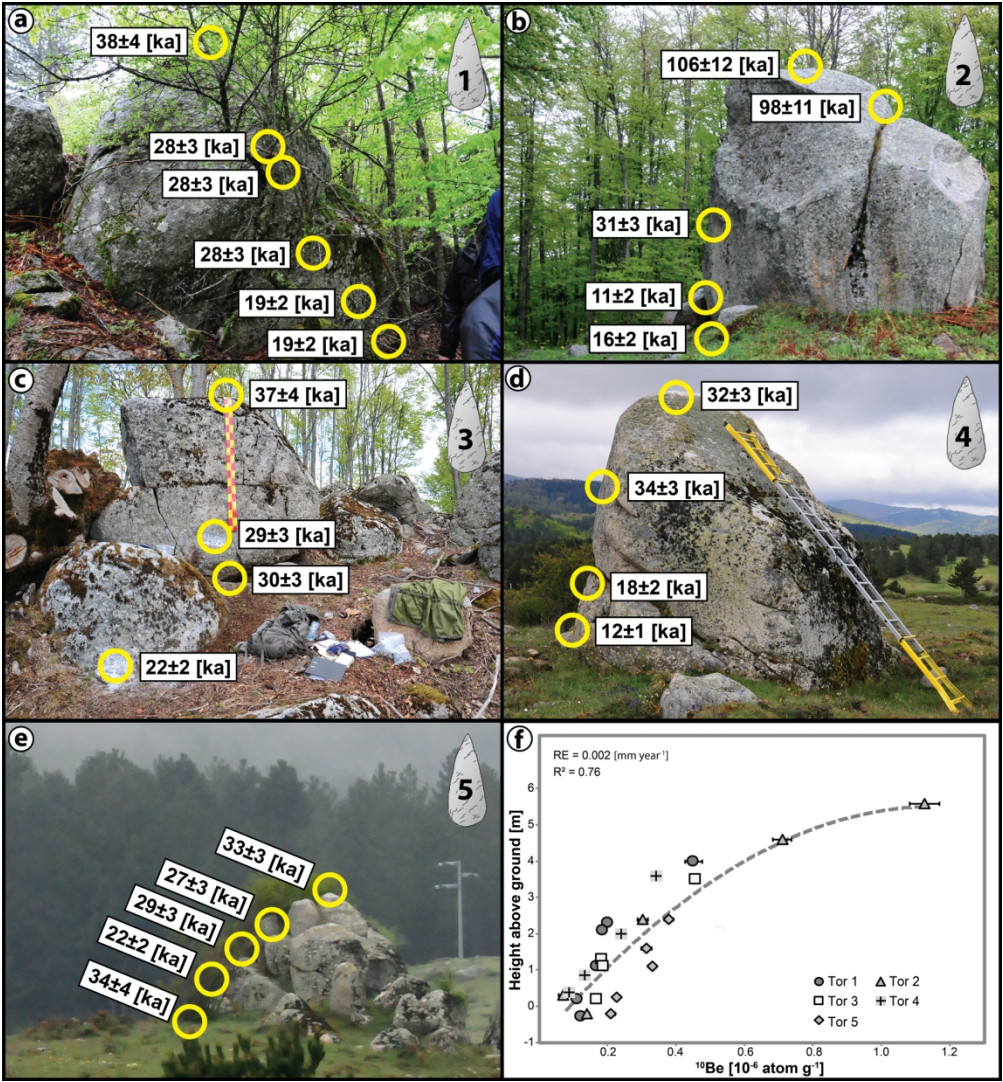


FIGURE 6 Exposure ages (a,b,c,d,e) along the tor profiles (Table 2). The overall ^{10}Be concentrations as a function of height (with related trend curve) of all samples are plotted in (f.)

702x756mm (72 x 72 DPI)

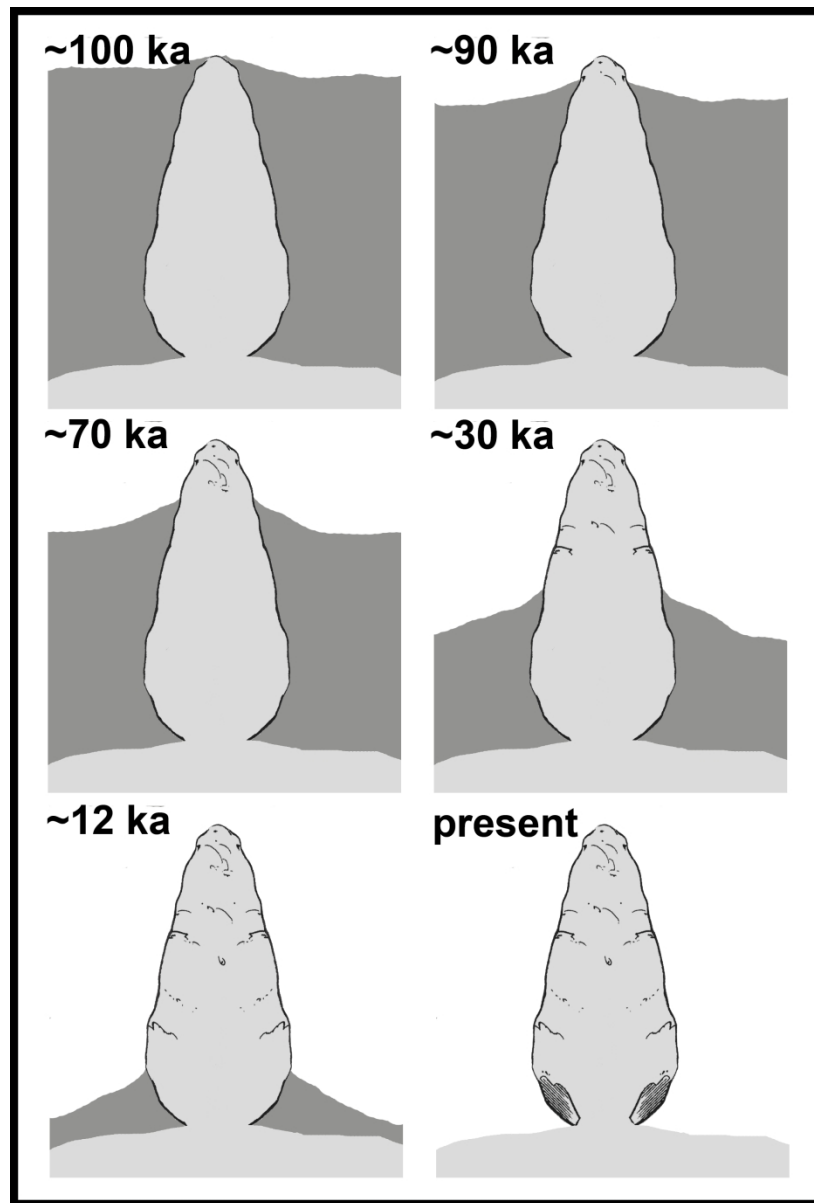


FIGURE 7 Concept of tor exhumation according to the surface exposure ages (e.g. Tor #2).

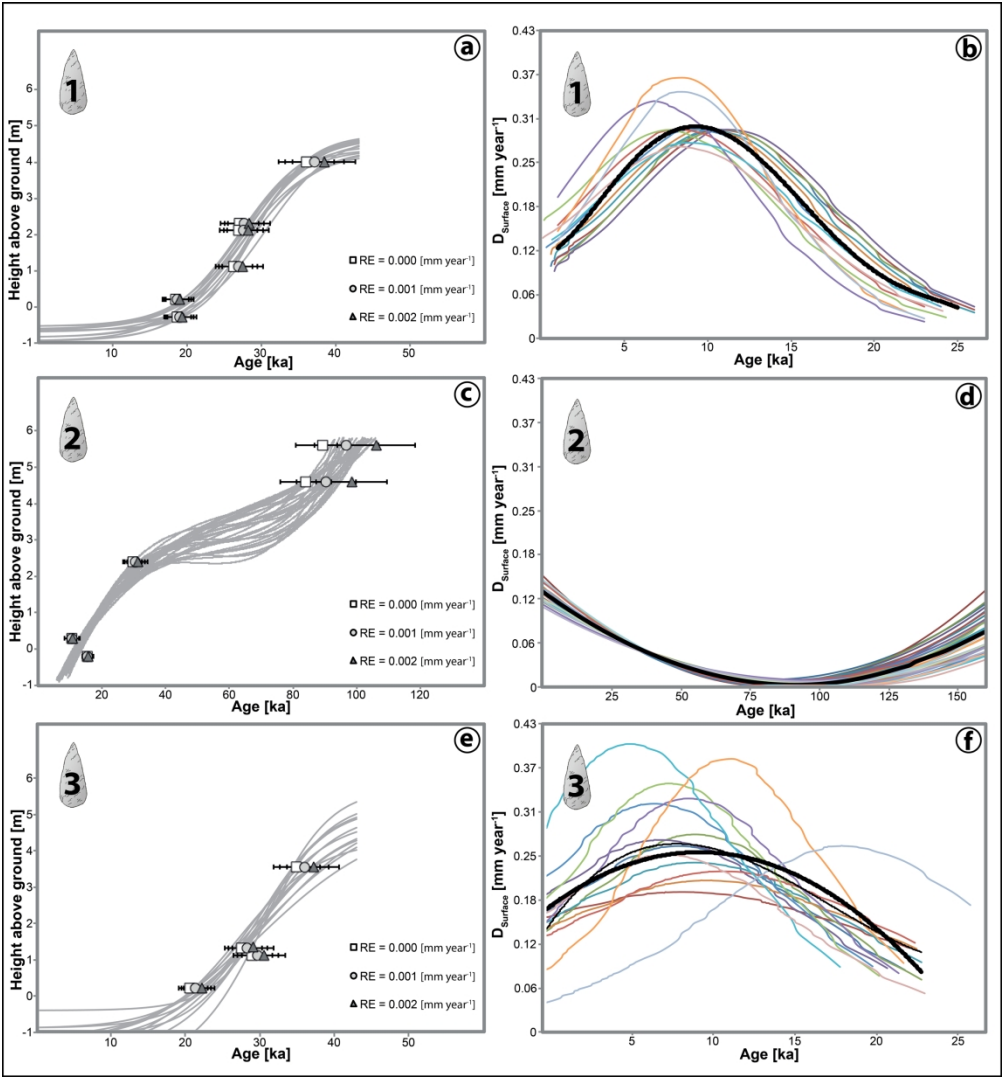


FIGURE 8 Trend of Exposure ages as a function of tor height and derived soil denudation rates ($D_{Surface}$) using Monte Carlo simulations for Tor #1 (a and b), Tor #2 (c and d) and Tor #3 (e and f). RE = rock erosion.

934x1004mm (72 x 72 DPI)

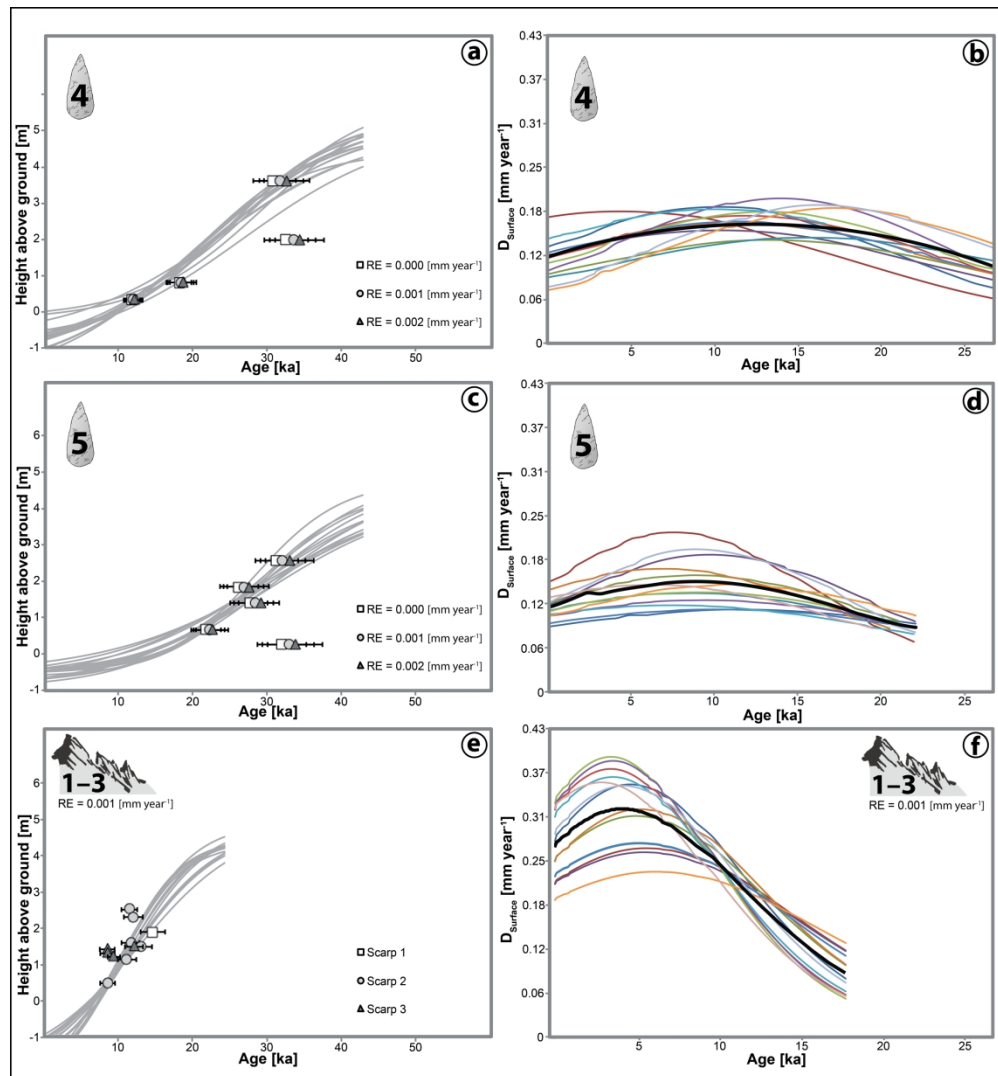


FIGURE 9 Exposure ages as a function of sample height /tors and scarps) and derived surface denudation rates (D_{Surface}) using Monte Carlo simulations for Tor #4 (a and b), Tor #5 (c and d) and Scarps #1-#3 (e and f). RE = rock erosion.

934x1003mm (72 x 72 DPI)

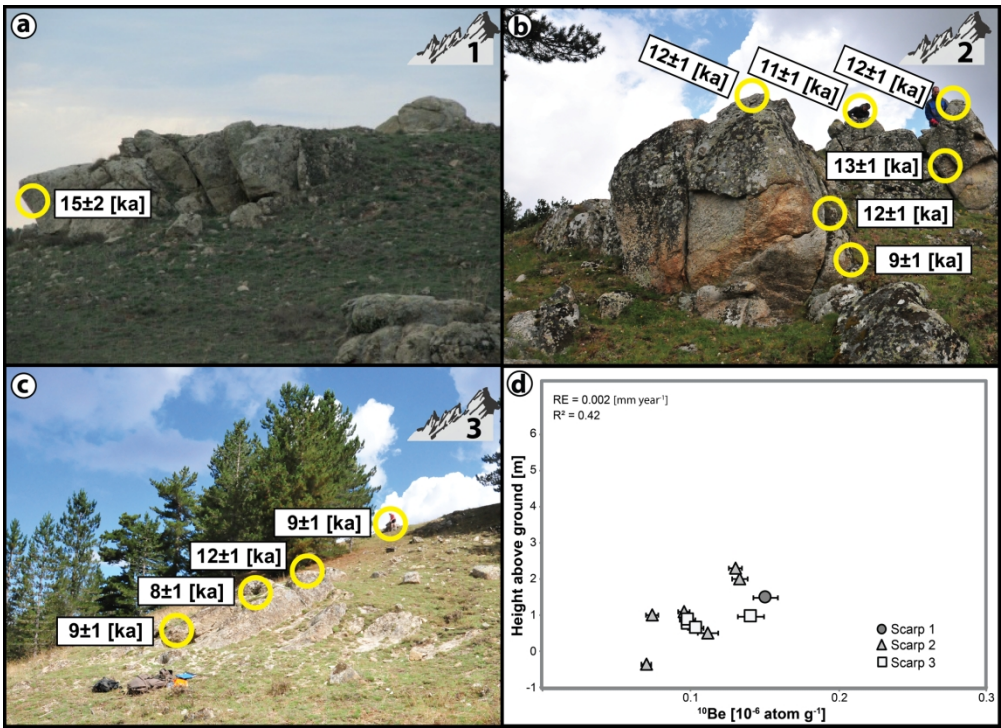


FIGURE 10 Exposure ages (a – c) of scarps (Table 2). Their ^{10}Be concentrations are plotted as a function of height (with related trend curve) in d).

819x591mm (72 x 72 DPI)

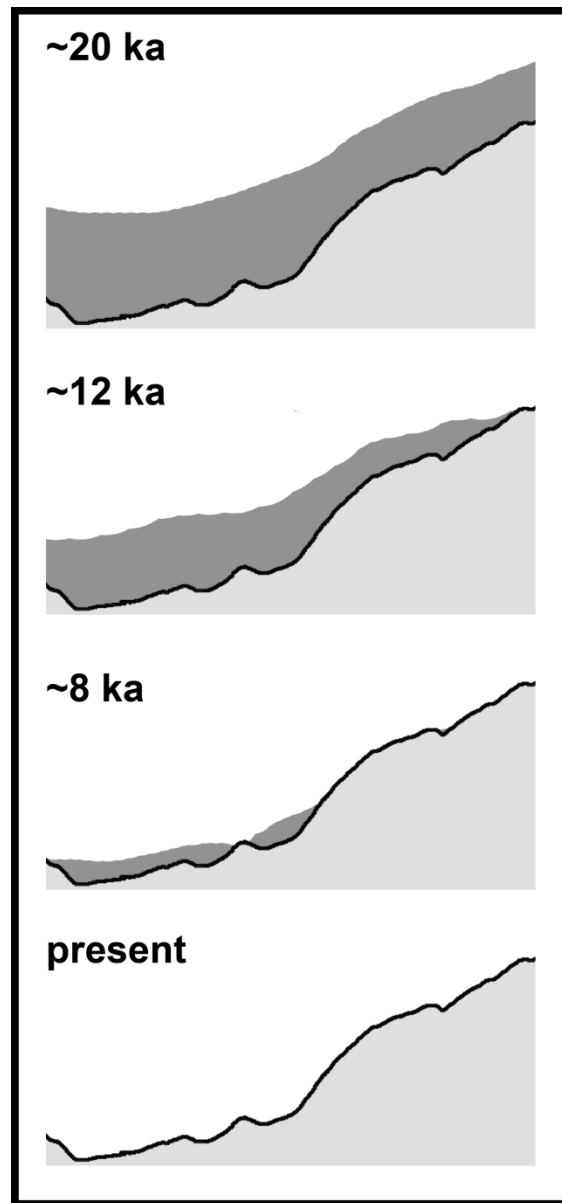


FIGURE 11 Conceptual model of surface lowering and exposure of scarps along the inner hills of the upland plateau.

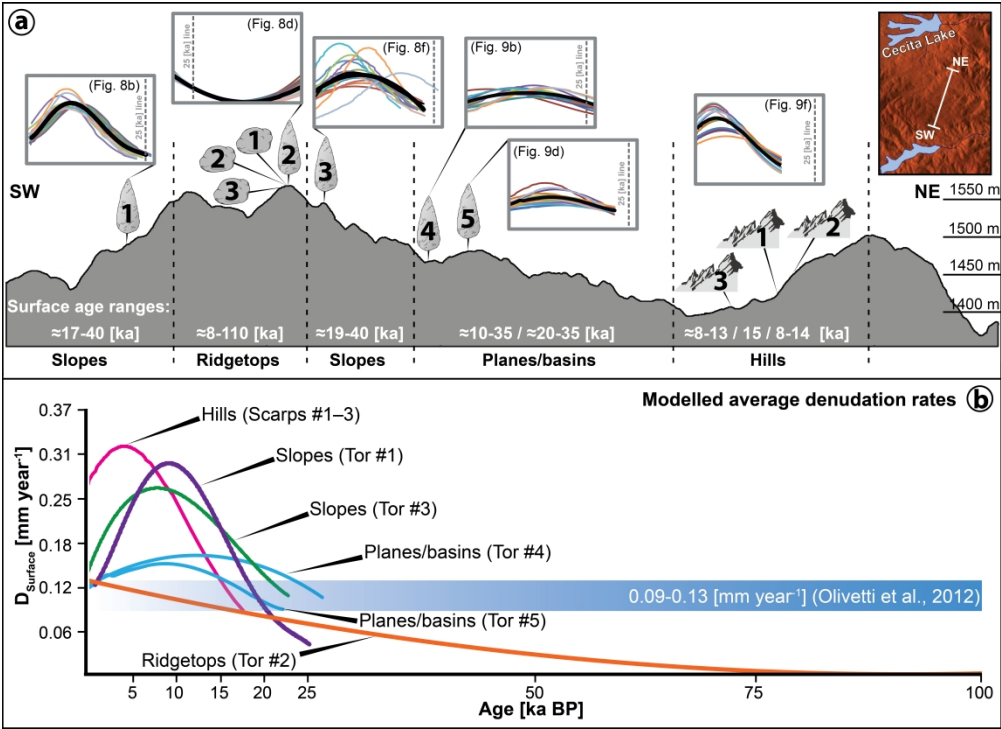


FIGURE 12 (a) Relation between surface topography and denudation rates along the SW-NE investigation transect. (b) Comparison of modelled average denudation rates over time (Fig. 8 & 9) of the different surface relief sections (e.g. ridgetops, slopes, planes/basins, hills) and average erosion rates (calculated from cosmogenic ^{10}Be concentration using a material density of $2.6 \text{ [g cm}^{-3}\text{)]}$ after Olivetti et al. (2012).

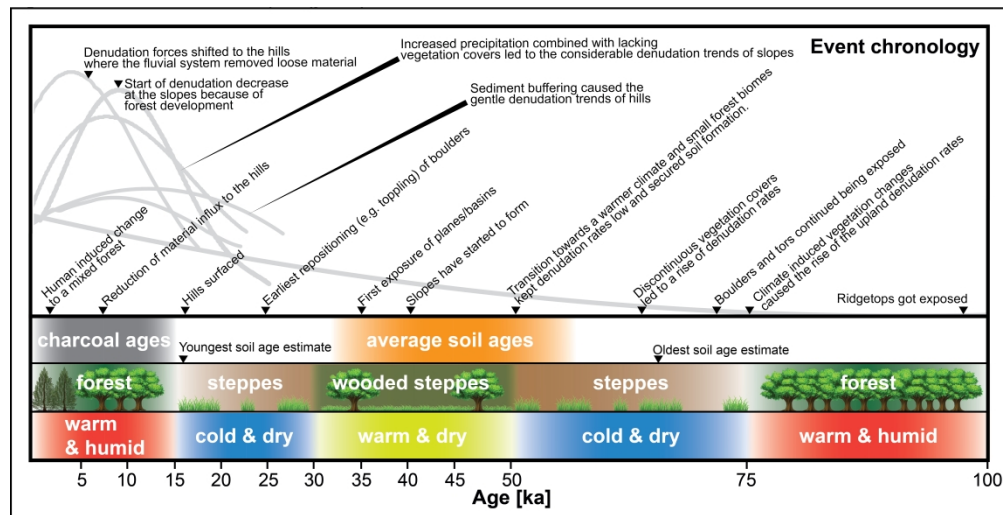


FIGURE 13 Model of local changes in climate (Allen et al., 1999) and vegetation (Allen et al., 1999; Pelle et al., 2013) for the last 100 ka. This concept also includes soil and charcoal ages and major findings of Raab et al. (2017) and Moser et al. (2017) to complement the series of surface evolution events.